Design and Development of Cold Gas Propulsion System for Smart Space Robot

P. Arunkumar, G. Mahesh, B. Ajith, Ebin Thomas, and Aishwarya Shankhdhar

Abstract Future human-space exploration efforts aim to achieve maximal synergy between human and robotic missions, where in human-scale robots shall supplement astronaut exploration activities and also undertake robotic precursor missions. Towards this, design and development of a flying Smart Space Robot (SSR) is initiated. The Smart Space Robot (SSR) is a space flying robot which will be tethered to the unmanned orbital platform on the fourth stage (PS4-UOP) of Polar Satellite Launch Vehicle (PSLV) for micro g experiments. SSR is of nano-satellite class with dimensions of ~350 × 350 × 350 mm, weight of ~12 kg and power of ~30 W. The nanosat has to undergo different phases of operations which include deployment, station keeping, retrieval and docking. These manoeuvres calls for a robust system capable of operating for an extended duration with multiple restart and pulsing capability. This paper details out the development and design process of a cold gas system within the constraints of space, volume, mass, voltage and power as designated by the nanosat specification which meets the mission requirements.

Keywords Nanosat. PSLV · Orbit manoeuvre

1 Introduction

While considering small satellites for a wide range of earth orbit and even interplanetary missions, cold gas propulsion systems are quintessential. Cold gas systems are excellent where a low total impulse is required with not much bothering about specific impulse. These systems are often used in small satellites since 1960's [1]. It has proven to be the most suitable and successful low thrust space propulsion for Low

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R.S. Priyadarshini and T. Sundararajan (eds.), *Advances in Small Satellite Technologies*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-19-7474-8_11

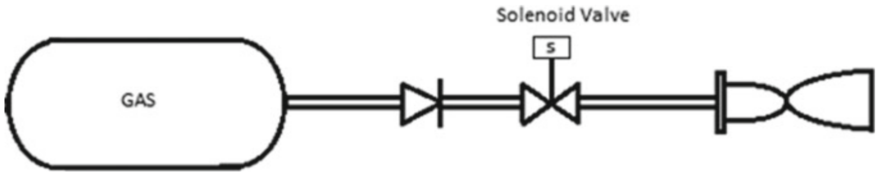

Fig. 1 Schematic of cold flow propulsion system

Earth Orbit (LEO) manoeuvres, due to its low complexity, efficient use of propellant which presents no contamination and thermal emission besides its low cost and power consumption. The notable advantages obtained from cold gas systems are low budget, mass and volume. The system mainly consists of a propellant tank, solenoid valves, thrusters, tubing and fittings [2] (Fig. 1).

The propellant tank is used to store the fuel required for attitude and orbit control of satellite during its operation. The propellant used in cold gas systems is compressed gas. Thrusters provide sufficient amount of force to provide stabilisation in pitch, yaw and roll movement in case of satellite and can also impart to or kill the velocity of spacecraft in translational direction. From the perspective of design, three components that play an important role of cold gas propulsion systems are mission design, propellant storage and cold gas thruster [2].

2 Design and Development

The development of a thruster is multifaceted optimisation problem taking into consideration the manoeuvers required in the mission. The system has to perform within the constraints of limited space, weight and power and convert the energy stored as pressure into kinetic energy of the nanosat. For the same, the design stage is initiated by taking the requirements of the mission and designing a system within the constraints and bounds of the mission.

2.1 Selection of Working Fluid

It is of utmost importance to select which gas to use as the propellant. This affects component selection in terms of sizing and materials selection. Various gases have been used for cold gas propulsion like helium, carbon dioxide, butane, air and nitrogen. Selection between the several possible gas options was based on many different factors. Chief among them were inflammable/non-reactivity, availability of the gas and material compatibility [3]. The options were narrowed down to four gases that were considered in greater detail, as outlined below.

Carbon-dioxide (CO_2)

In systems where carbon-dioxide is used, it is stored in mixed liquid and gas phase. As the gaseous CO_2 is used as propellant, the liquid CO_2 evaporates to replenish it, keeping the pressure inside the propellant tank constant until all the liquid evaporates [4]. This helps in a constant tank pressure and stable thruster performance, and storage in liquid phase means that a relatively large mass of propellant can be carried with simple and light systems' design.

Helium (He)

Helium is one of the best cold gas propellant on account of its high-specific impulse. It has an Isp of approximately 180 s, which is very high for an inert gas propellant [5]. However, due to its low density, helium should be stored at very high pressure or requires a storage tank of higher volume. This often results in a heavier propellant tank and durable, leak proof plumb lines capable of supporting high pressures. Thus, the heavier system counteracts the gains from the high Isp. Furthermore, helium systems are especially prone to leaking on account of its low molecular mass. This requires specific materials driving up the cost of propulsion system.

Nitrogen (N_2)

Nitrogen gas has only a mediocre Isp of 60–80 s. It is strongly outclassed by helium in terms of efficiency. However, nitrogen is denser and less susceptible to leaking in comparison to helium which means the system design is lighter and less complex, and it is also cheaper. It is a common choice for cold gas propulsion systems in around the world.

Butane (N2)

Butane thrusters have similar ISP to GN2 thrusters but require lower storage envelope due to its higher density and conveniently, it can be stored at a very low pressure, hence no pressure-regulation system is required. Despite lower system weight, butane is more prone to liquefaction and there is a possibility of two phase flow which will result in lower ISP. To prevent this, heaters and plenum chambers have to be provided which complicates system. The system is also prone to sloshing.

Out of the numerous options, GN2 has been selected owing to its simplicity in handling and operations and its leak proof property.

2.2 System Specification

The cold gas propulsion system is designed to impart velocity to the nanosat for various manoeuvres. The thrusters will be used in the following phases of SSR operation:

- Imparting separation velocity—along deployment direction (4 s burn)
- De-tumbling and attitude disturbance rejection

- Killing of delta V
- Azimuth correction
- Station keeping
- Retrieval.

The nanosat performs 4 major operations and the total impulse requirement was estimated to be 100 Ns. The thrust generated by the proposed thrusters are 150 mN. This results in a total firing duration of 667 s. From the operating duration, the volume of working fluid required and tank volumes can be worked out.

2.3 Design of Thrust Chamber and Propulsion System

Thrusters are the convergent-divergent nozzles (Fig. 2) that provide desired amount of thrust to perform manoeuvres in space. The nozzle is shaped such that high-pressure low-velocity gas enters the nozzle and is compressed as it approaches smallest diameter section, where the gas velocity increases to exactly the speed of sound.

Nozzle Design (First Cut Calculation)

The thruster is operated in the vacuum and the following parameters are taken as design inputs.

Design parameters—thrust-Th (150 mN); chamber pressure-P_c (7 bar); and exit pressure $-P_e$.

By assuming an exit pressure, the expansion ratio (area ratio) can be found out by using,

$$\varepsilon = \frac{A_e}{A_t} = \frac{\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} * \left(\frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{2}}}{\left(\frac{P_e}{P_c}\right)^{\frac{1}{\gamma}} * \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}}} \tag{1}$$

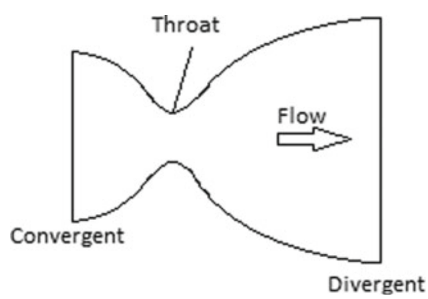

Fig. 2 Typical convergent divergent nozzle

The area ratio (ε) is limited by mechanical and envelope constraints. The ideal combination of the exit pressure (P_e) and ε is finalised after extensive iteration.

The exit Mach no (M_e) can be found by solving isoentropic relation,

$$\frac{P_e}{P_c} = \left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{\frac{-\gamma}{\gamma-1}} \tag{2}$$

The thrust coefficient (C_f) can be found by solving the equation,

$$C_f = \sqrt{\frac{2\gamma^2}{\gamma - 1}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} + \left(\frac{P_e - P_{\text{atm}}}{P_c}\right) * \varepsilon \tag{3}$$

Applying the above results in the thrust equation will yield the throat area (A_t)

$$T_h = P_c * A_t * C_f \tag{4}$$

The mass flow ($\dot{m}$) required for each thruster can be found by solving the chocked flow equation

$$\frac{\dot{m}}{A_t} = \frac{\Gamma * P_c}{\eta C d \sqrt{\gamma R T_c}}$$

where, r is the Van-Kirchhoff function

$$\Gamma = \lambda * \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{5}$$

All other major design parameters of the nozzle like throat dia (D_t) and exit dia (D_e) can be found by solving Eq. (1).

From the mass flow and the total duration of firing, major system parameters like the total volume of working fluid, tanks capacity, and plumb lines can be finalised.

Nozzle Design (CFD Route)

The nozzle design is also deduced using CFD tool. The results are satisfactory with the thrust imparted by the nozzle which is on the higher side with 180 mN as compared to 150 mN.

- Geometric Modelling and Meshing
- Actual 2-D model of Cold Gas thruster and far-field (15 d horizontal and 5 d vertical) created in AUTOCAD
- AUTOCAD model imported to POINTWISE
- Approx. 35,000 nos. nodes considered for solving the problem
- Mesh file was imported to FLUENT for CFD analysis (Fig. 3).

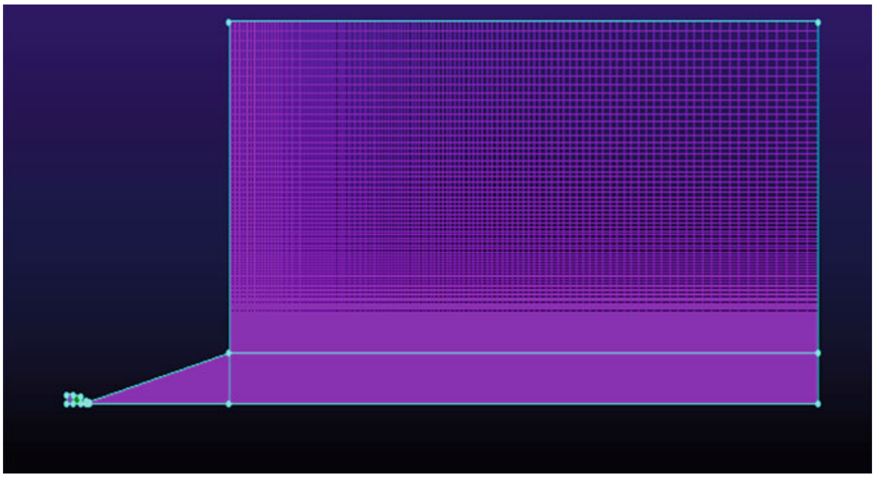

Fig. 3 Cold flow thruster meshed in POINTWISE

Governing Equations

(1) Mass Conservation Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial zx} = 0 \tag{6}$$

(2) Momentum Conservation Equation

$$\rho \frac{Du}{Dt} = -\frac{\partial \rho}{\partial x} + \frac{\partial}{\partial x}\left[2\mu \frac{\partial u}{\partial x} + \lambda \mathrm{div} u\right] + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right] + S_{Mx} \tag{7}$$

(3) Energy Conservation Equation

$$\rho \frac{DE}{Dt} = -\mathrm{div}(\rho u) + \left[\frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z}\right] + \mathrm{div}(\mathrm{kgrad}\ T) + S_E \tag{8}$$

Method of solution

- Density based Solution
- 2-D Axisymmetric
- SST K-Ω turbulence model.

Table 1 CFD results

Sl. No.	Parameters	Results
1	Thrust (N)	0.153
2	Mass flow rate (mg/s)	224
3	Exit pressure (Pa)	21
4	Exit Mach No	10.3
5	Cd at throat	0.96

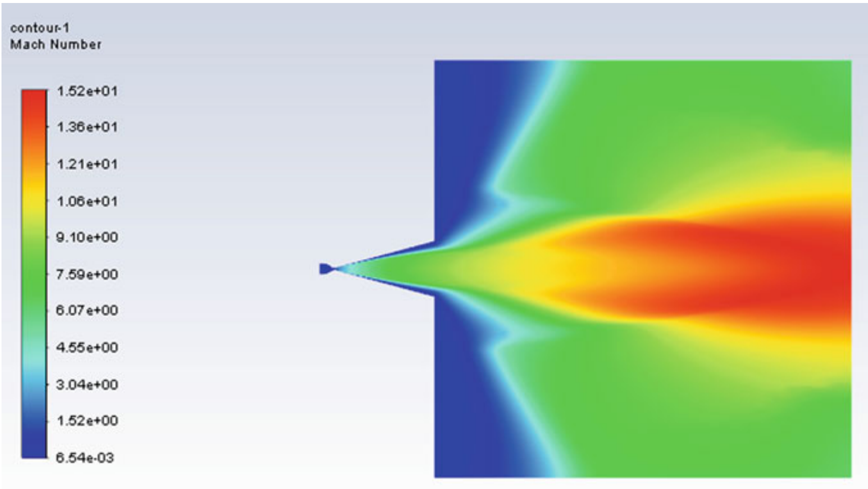

Fig. 4 Mach number contour

The CFD analysis results are shown in Table 1, and the contours are shown below (Figs. 4 and 5).

2.4 *Thruster Valve*

Thruster valve controls the operation of the thrusters. The valve must be robust and capable of multiple operations so as to fulfil various mission operations. Figure 6 shows the valve assembly together with the thrust chamber. The valve is an ON/OFF solenoid valve. The valve operates by opening and closing an armature using the magnetic flux generated by a solenoid coil.

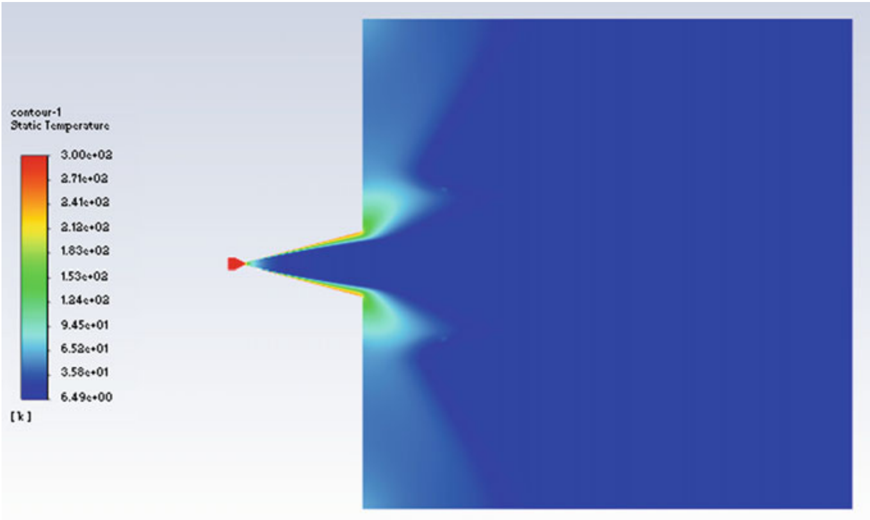

Fig. 5 Static temperature contour

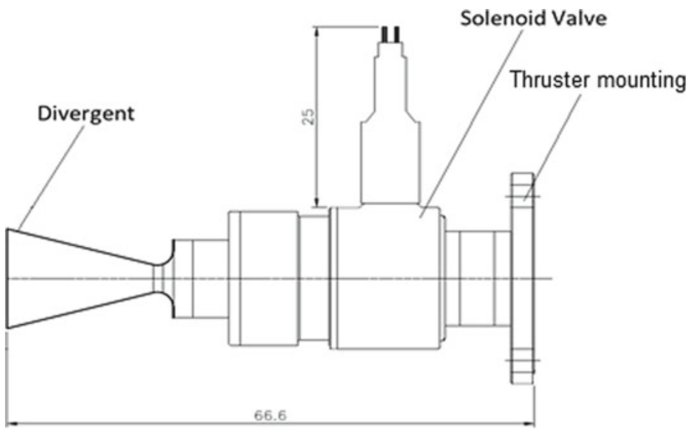

Fig. 6 Thruster assembly

2.5 *Propulsion System Design and Configuration*

The propulsion system stores the working fluid in pressurised condition and delivers it at reduced pressure to the thrusters when they are operated.

Mass of the gas required can be calculated from the total duration and mass flow per thruster.

$$\text{Total Propellant Mass } (Mt) = \text{Mission duration } (t) * \text{flow rate } (\dot{m}) \tag{9}$$

The total mass of propellant required is approximately 150 g. The tanks and plumb lines will be pressurised to a pressure of 70 bar before the mission and the thrusters will be operated at blowdown mode. The total volume required when the gas is stored at a pressure of 70 bar is as follows:

$$\text{Total Gas Volume},\ Vt = 1929.2\ \text{cm}^3$$

The propellants are generally loaded into the satellite with a loading factor of 1.3. The loading factor signifies the amount of propellant in the tank. A loading factor of 1.3 is imperative to an extra mass by 30% in the tank than required for the mission. This extra mass will be utilised to impart the pressure for the gas till the end of life of the satellite. Hence, the total mass of propellant required is 200 g and the volume of tank required for SSR is as follows:

$$\text{Required Gas Volume},\ Vt = 2440\ \text{cm}^3/2.44\ \text{ltr}$$

A singular propellant tank of 2.6 L has been conceived to cater the requirements of cold gas thrusters. The tank will be mounted centrally in the SSR.

Pressure regulation

The thrusters will be operated on regulated mode. Electronic pressure regulator (EPR) is sought after to regulate the downstream pressure irrespective of the upstream pressure. The upstream pressure varies from 70 to 35 bar during the course of the mission but the EPR will regulate the downstream pressure to 10 bar. An EPR consists of a piezo-electric valve with a pressure transducer downstream to provide the closed loop feedback system to ensure a regulated downstream pressure. In the present case of Cold Gas propulsion system, the EPR imparts desired regulated pressure of 10 bar which is critical in ensuring constant thrust of thrusters.

Latch Valve

A latch valve is also introduced downstream of EPR to arrest any possibility of leak to happen. This ensures that the FCV which is upstream of thrusters will not experience undesired pressure of 70 bar because the FCV is designed for an MEOP of 10 bar.

The finalised configuration of propulsion system is shown in Fig. 7. The system employs an electronic pressure regulator (EPR) which is to regulate the downstream pressure irrespective of the upstream pressure. A latch valve (LV) is introduced downstream of EPR to arrest any possibility of leak to happen. This ensures that the FCV which is upstream of thrusters will not experience undesired pressure of 70 bar because the FCV is designed for an operating pressure of 10 bar. The volume between the EPR and latch valve is maintained very less, in case of a pressure rise due to the leak; the large downstream volume will negate the high-pressure rise at the FCV inlet (Fig. 8).

The thrusters are configured around the thrusters in order to cater to its various manoeuvring requirement and only four thrusters can be operated at a time due to various constraints placed due to flow and power.

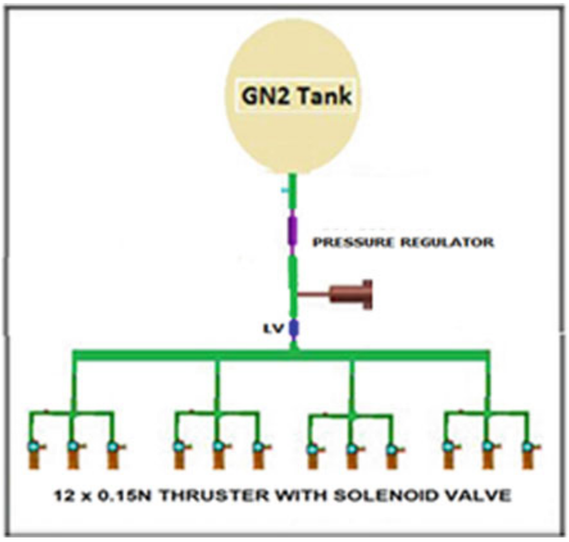

Fig. 7 Propulsion system schematic

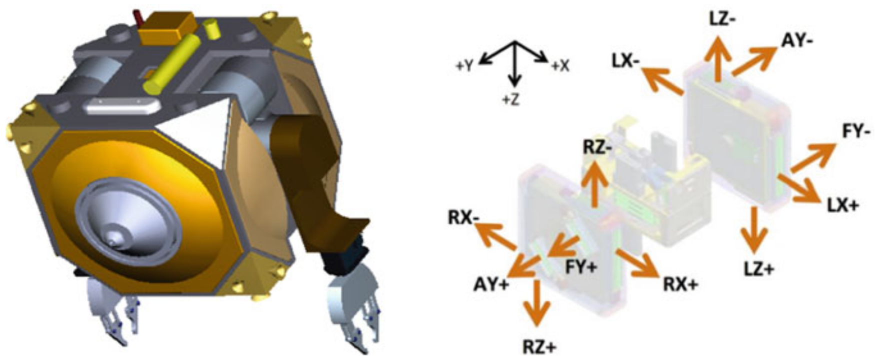

Fig. 8 Configuration of thrusters around SSR

3 Criticalities

At the onset of design phase, many criticalities were faced by the design team. The constraints placed by space, mass, low power and pressure called for devolvement of new systems and major modifications on existing system. Existing propulsion components used were carefully analysed and trade-offs were studied to meet project requirement. The major criticalities are discussed below,

3.1 Space and Mass Management

The initial available volume for propulsion system was 1 L. While considering a loading factor of 2, this called for propellants to be stored at 400 bar pressure. But after rigorous reconfiguration of components and redesign of the subsystems, the space was increased to 2.6 L. In addition, it was decided that a loading factor of 1.3 would be adequate since the mission duration is only 667 s. This reduced the pressures to 70 bar which is a comfortable value and gave confidence to the system designers.

Mass of the system is also an important constraint. Though the initial mass requirement specified a max of 3 kg for propulsion system, with the introduction of pressure regulation and pressure measurements, the mass of the propulsion system has increased to 5 kg. The trade-off between mass and reliability of the system was analysed, and it was decided to accommodate the higher mass of propulsion system.

3.2 Power Management

The lower power generated is a major constraint when designing system for nanosat. The power requirement of available solenoid valves was higher that the power supply capability. Amelioration of the power supply and miniaturisation of existing solenoid valve enabled to scarcely meet the power requirement.

3.3 Pressure Management

The constraint on the tank pressure indirectly comes from space constraint. The initial volume of 1 L was increased to 2.6 L after reconfiguration of subsystems, and storage pressure was reduced to 70 bar. It was also very significant to finalise a system for pressure drop management from 70 bar in tank to 7 bar in thrusters. In this regard, two types of system were sought after: the one was with conventional multiple orifice system and the another one was a regulated system using an Electronic Pressure Regulator (EPR).

The orifice system was considered owning to its simplicity and low mass. But on careful analysis, it was found that orifice system was unsuitable because of the repercussions of choking occurrence upstream of the thruster throat. Thus, a pressure-regulated system was selected in spite of higher mass since it provides more reliable performance.

4 Conclusion

Although cold gas thrusters are simpler compared to other propulsion systems, it still contains various constraints like volume envelope, simplicity, power constraints, voltage constraints and mass which makes it a complicated optimisation problem. In addition to that, the requirement of multiple restarts calls for a robust and versatile system. This paper lists out various constrains and thought process in the design phase of the cold gas system which uses a GN2 gas as working fluid and within the operating duration of 667 s.

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